Research Article

ATTENTIONAL DEMANDS FOLLOWING PERCEPTUAL SKILL TRAINING

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Abstract—*Practicing simple visual tasks induces substantial improvement. We investigated whether increased efficiency is accompanied by automaticity and immunity to across-task interference. We found that although practice speeds orientation feature detection, it does not abolish susceptibility to interference from introduction of concurrent central-letter identification, which takes priority. Yet following training with each task, observers successfully managed to perform the tasks concurrently. The effectiveness of separate training implies that the role of improved intertask coordination in achieving concurrent performance was minor. Indeed, even when initial training was concurrent, improvement on the two tasks was sequential, and the higher-priority (central) task was learned first. However, automatic processing was not accomplished either, because increasing the difficulty of the higher-priority task interfered with performance of both tasks. What appears to be orchestrated posttraining performance is actually mainly an emergent property of speeded initial processes rather than either eliminated bottlenecks or improved central executive management.*

Everyone is familiar with the frustrating experience of trying to do more than one thing at a time. At the same time, everyone has witnessed how this “juggling” act becomes possible with practice. What are the mechanisms underlying increased capacity? Do people learn juggling management? Alternatively, is juggling no longer required because each task becomes ballistic, with a triggering command sufficing for it to proceed to fulfillment?

It is not only intuition but also expert theories that diverge with respect to these issues. In the 1970s, Shiffrin and Schneider suggested that the effectiveness of practice might lie in its strengthening consistent stimulus-response mapping. If subjects are trained with fixed targets, identification becomes automatic regardless of stimulus complexity. Subsequent performance may be immune to introduction of a concurrent task because it no longer requires voluntary allocation of limited resources (Shiffrin & Schneider, 1977; see also LaBerge, 1973; Steinman, 1987).

Other researchers questioned the source of initial intertask interference (e.g., Navon & Gopher, 1979). They suggested that between-task interference arises at specific processing points rather than as a result of competition for a single pool of limited resources. Theories differed with respect to the location of this bottleneck where two tasks cannot be performed in parallel. Different suggestions placed it at choosing a motor response (Gopher, Brickner, & Navon, 1982; Keele, 1973), making abstract decisions (Pashler, 1994), or encoding percepts to working memory (De Jong & Sweet, 1994; Jolicoeur, 1999);

some theories even placed it at an earlier perceptual level (Broadbent, 1971; Duncan, 1980; Treisman, 1969). In principle, these views are not mutually exclusive because there could be more than one limiting processing stage (Allport, 1993; De Jong, 1993; Meyer & Kieras, 1997). It seems that interference stems from competition, not conflict, because it has been found for cases in which there is no response incompatibility, for unrelated motor responses, and even when tasks involve different stimulus categories or modalities (e.g., visual and auditory; Jolicoeur, 1999; but see Duncan, Martens, & Ward, 1997).

Although Shiffrin and Schneider (1977) suggested that an adequate (consistent stimulus-response) training procedure should suffice for a trained task to acquire ballistic properties, other researchers categorically disagreed. They suggested that the introspective sense of effortless performance results from optimizing strategies and rearranging elements of task performance (Cheng, 1985). Various specific mechanisms were suggested for this restructuring. These included chunking, whereby the basic unit of information is enlarged, making processing more efficient (Newell & Rosenbloom, 1981); precompiling a sequence of computational steps required for a task (perhaps a form of chunking; Anderson, 1982); or replacing computation altogether by memory retrieval (Logan, 1988; see Treisman, Vieira, & Hayes, 1992). If training restructures processing but does not reduce attentional needs, how do people ultimately achieve seemingly simultaneous performance of concurrent tasks? These theories suggested that they do not. Rather, people learn only to juggle tasks better. Specifically, it was suggested that restructuring might involve a central executive function, which directs and orders processing elements to achieve better integration and seemingly seamless performance (Baddeley, 1990; Norman & Shallice, 1986).

The aim of the current study was to determine which if any of these alternatives underlies successful dual-task performance in the case of simple and well-trained perceptual tasks. Is successful dual-task performance the result of concurrent independent processing (as suggested, e.g., by Shiffrin & Schneider, 1977), and if not, what does improve to yield the deceiving appearance of concurrent processing?

As our test case, we chose two simple visual tasks: central-letter identification and odd-element orientation detection. The latter task was chosen for two reasons. First, we had found previously a striking improvement when subjects were trained to detect an oddly oriented bar in a field of homogeneously oriented distracting bars. That is, processing time required for a reliable answer decreased dramatically with training (Ahissar & Hochstein, 1993, 1996, 1997b). Second, even though orientation detection is a simple “early vision” task, it was recently shown that initially—that is, before training—such detection may be markedly degraded by introduction of a concurrent visual task (Braun, 1998; Joseph, Chun, & Nakayama, 1997). Thus, we wanted to know if simple tasks, which may initially interfere but whose performance can be improved, would become independent or at least appear to do so after training. (Preliminary results of this study have been

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METHOD

The four experiments we report here all used variations of the same tasks.

Stimuli

For the odd-element orientation detection (pop-out) task, a 7×7 array of light bars was presented, as demonstrated in Figure 1. An odd-element target was or was not present, with equal probabilities. Depending on the experiment, this target was lateral to or diagonal from fixation. Target and distractor orientations were 30° and 60° , respectively, for half the subjects, and vice versa for the other half. For the letter identification task, a letter, *T* or *L*, was presented in the center of the array, in one of four orientations.

In Experiment 3, the stimuli were manipulated after initial training. As shown in Figure 1, the target and distractor orientations were

swapped, or the letters to be identified were replaced with the tail or head of an arrow (Υ or $\uparrow$).

Temporal Sequence

To minimize response-selection interference, we used masked stimuli and measured the effect of stimulus-to-mask delay on performance accuracy (rather than reaction time). The lower-right illustration in Figure 1 indicates the temporal sequence of the trials. In response to a fixation cross, subjects pressed a key to indicate they were ready. After that, a blank screen was presented for a variable period of 120 to 165 ms, and then the stimulus display appeared. A 166-ms mask followed the stimulus after a variable stimulus-to-mask onset asynchrony (SOA). The screen then went blank for 233 ms before the fixation cross reappeared. Subjects then pressed a response key to indicate presence or absence of an odd element, letter identity, or both. For the dual-task condition, half the subjects were instructed to first identify the central letter, and half were instructed to first indicate the presence or absence of an oddly oriented element. A pleasant computer tone rewarded each correct response. (See Ahissar & Hochstein, 1993, 1996, 1997b, for details.)

Sessions comprised 1,400 trials (70 blocks of 20 trials, each with

Fig. 1. Stimuli and trial temporal sequence for the dual-task paradigm, which included odd-element detection and central-letter identification tasks. Following training, target and distractor element orientations were swapped or the letters (*T*, *L*) were changed to the head and tail of an arrow ($\uparrow$ and Υ), to test intertask interference effects. The top row shows arrays with and without an odd element, an array with an odd element in the condition in which we swapped orientations of the target and distractor elements (Experiment 3), and the mask that followed the arrays; the bottom row shows arrays with and without the odd element when the arrow head and tail were used in place of letters. The trial temporal sequence shows the timing of the fixation cross, stimulus and mask presentation, and the blank screen between them. (See the text.) SOA = stimulus-to-mask onset asynchrony.

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a fixed SOA) when a single task was performed, and 1,000 trials (50 blocks of 20 trials) when the two tasks were performed. We measured percentage correct for each SOA, often averaging results for all long SOAs (83–183 ms). Chance performance was 50% correct.

RESULTS AND DISCUSSION

Experiment 1

The strong version of acquired automaticity asserts that sufficient training will render task performance immune to introduction of a second task. To test this independence for a very simple detection task, we measured the effect of extensive odd-orientation detection training on performance when a central task is added. A group of subjects was trained on odd-element detection for 10 to 20 sessions. When a large orientation difference is used, this task is simple, and the odd element “pops out” effortlessly with free viewing (Julesz, 1981; Treisman & Gelade, 1980). The version of the task we use is more difficult, with brief presentation and subsequent masking (Ahissar & Hochstein, 1993, 1996). Yet we expected that the detection performance of well-overtrained subjects would be unaffected by performance of a concurrent task. The latter task was identification of a letter (*T* or *L*) presented at the point of fixation (Fig. 1). We found, however, that consistently, for all subjects, performance dropped dramatically, as shown in the top panel of Figure 2 (for long, easy SOAs, performance dropped from 100% to 62% correct, $p < .01$; for shorter SOAs, performance dropped from 96% to 59% correct, $p < .001$). Still, a period of combined practice yielded successful dual-task performance.

We conclude that training a single simple task does not free its performance from initial bottlenecks. What, then, does concurrent practice later modify to ultimately enable successful performance? One possibility is juggling—better central executive management of the combined situation. Alternatively (or additionally), practice might simply speed processing at stages preceding or involving the interference bottleneck. In the first case (central executive), it would be specific practice with the dual-task situation that allows ultimate successful performance. According to the second alternative (speeded processing), separate training of each task should be just as effective for achieving successful dual-task performance. The next experiment was designed to differentiate between these alternatives.

Experiment 2

We trained another group of subjects first with orientation detection and then with *T-L* discrimination. Consequently, they were skilled in each task, but had no prior experience with performing the tasks concurrently. Following these separate training sessions, the subjects' dual-task performance was quite successful right from the beginning, as shown in the bottom panel of Figure 2. The drop in orientation detection performance upon introduction of the dual-task condition was considerably smaller than the drop that occurred in subjects who had no previous *T-L* training (for long SOAs, the drop was to 85% correct, compared with 62% without prior *T-L* training, $p < .05$; for short SOAs, the drop was to 73% rather than 59%, $p < .05$).

Still, performance was not quite as good as at the dual-task asymptote (for long SOAs, 85% compared with 96%, $p < .01$; for short SOAs, 73% compared with 82%, n.s.). A small remaining improvement was achieved rapidly once concurrent practice was introduced. Thus, although the central executive contributes to total success under the combined condition, its role is smaller than the role of speeded processing. The major requirement for successful dual-task performance is separate improvement in each of the tasks. It seems that the bottleneck is avoided mainly by speeded performance, not by its elimination.

If the major source of reduced intertask interference following practice is increased efficiency at or before the (enduring) processing bottleneck, then successful dual-task performance does not express independent processing. Each of the two tasks has just become easier, not automatic. In this case, even following massive training, if the task that gains prior access to the limiting process becomes harder, then performance of the other task should be hampered. Alternatively, if by some additional mechanism the combined practice eliminates the bottleneck altogether, then making one task harder should affect performance of that task but not of the second task. Our finding of substantially reduced interference following separate training is consistent with the first alternative and suggests that making one task harder will reintroduce cross-task interference.

Experiment 3

To test this prediction, following dual-task training we made the tasks harder again by modifying the stimuli. Previous studies had indicated that learning is largely specific to the trained stimuli (reviewed in Ahissar & Hochstein, 1998). We therefore expected that changing the stimuli for one task would degrade its performance. Thus, changing the orientations of the array elements was expected to degrade performance in orientation detection (Ahissar & Hochstein, 1993, 1997b), whereas changing the central letters was expected to degrade letter identification. We asked if these changes would also renew cross-task interference.

We found an asymmetric pattern of interference. Changing array elements by swapping the target and distractor orientations hampered orientation detection but had no effect on letter identification (Figs. 3a and 3b). In contrast, changing the identification task from *T-L* discrimination to Υ - $\uparrow$ discrimination hampered performance of both tasks (Figs. 3c and 3d). This pattern of interference suggests that even when dual-task performance is almost as good as single-task performance, processing still requires (limited) attentional resources. In this case, the task that received priority, either by being performed first or by receiving more attentional resources, was central-letter identification. It is this priority setting that determined the direction of the asymmetric cross-task effect. Note that the central-letter task received priority also before it was trained, in that its introduction (following orientation detection training) obstructed performance of the trained task (Fig. 2, top panel). The source of the letter-task preference may be that the letters were at fixation whereas the detection task required spreading attention to the whole array.

We tested if priority setting would also affect the order in which the tasks were learned. We trained 9 additional subjects under dual-task conditions and examined the performance of both these naive subjects and those in Experiment 3 to determine whether training was

Fig. 2. Results for Experiments 1 and 2: Average percentage correct for subjects who first were trained on the orientation detection (pop-out) task, and then were tested and retrained with concurrent orientation detection and letter identification (*T* vs. *L*). The top panel shows average data for 4 subjects trained on odd-element orientation detection and then on the dual task. The bottom panel shows average data for 7 subjects trained on both the orientation detection and the letter identification tasks, separately, before the dual-task performance. Difficulty of the pop-out task differed for the two groups in that the target was at an easier location (lateral to fixation) for the former group and at a more difficult location (diagonal from fixation, as in Fig. 1) for the latter group. Blocks consisted of 20 trials each, with the same stimulus-to-mask onset asynchrony (SOA). Only data for long SOAs (83–183 ms) are shown. Vertical bars separate testing sessions.

effective for the two tasks simultaneously or subjects learned one task at a time. Had dual-task performance depended mainly on experience with the dual-task condition (e.g., via improved central executive control or abolished interference), we would have expected that original dual-task training would affect both tasks together (e.g., via the central executive). But because we found that dual-task performance depends mainly on learning each of the tasks, we expected that even dual-task training would affect the tasks separately, one after the other. In this case, which would be affected first? Because of the priority of the central-letter task in Experiment 3, we predicted that performance of this task would be the first to improve during dual-task training.

Experiment 4

As predicted from the powerful effect of separate training, we found that even concurrent practice results in sequential learning. Though we asked subjects to perform both tasks in each trial right from the beginning, improvement on one task was almost always separate from improvement on the other (19 of 20 subjects; 1 subject learned the tasks simultaneously). Consistently, subjects mastered letter identification at fixation within a few training blocks, while performance of odd-element detection remained at chance level. Then there was a period lasting a few hundred to a few thousand trials during which performance with the central-letter task was perfect and

Fig. 3. Results for Experiment 3: Dual-task performance for subjects who had mastered the dual task when the tasks were made harder by stimulus manipulations. Results are shown separately for the orientation detection (pop-out) task and letter identification task when the orientations of the target and distractor were switched (a, b) and when the letters to be identified (*T* and *L*) were replaced by *Y* and *↑* (c, d). The data shown are for the first third of the session (i.e., the first 340 trials). Each point on the scatter plot represents performance by 1 subject, comparing performance before (abscissa) and after (ordinate) the modification. Points falling below the right diagonal indicate degraded performance due to the modification. SOA = stimulus-to-mask onset asynchrony.

yet no improvement was apparent in performing the orientation detection task. Only later did improvement begin in the detection task, as demonstrated by the examples in Figure 4. Task learning in this case seems to require undivided attention. Overtraining on one task (*T-L* discrimination) may be required to speed its performance sufficiently so that attention is freed rapidly for learning the other (orientation detection). The order in which the tasks were learned did not depend on the order of the response. Half the subjects gave their response for orientation detection first and their response for letter identification second, and the other half answered in the reverse order. Nevertheless, the central-letter task took priority in securing the undivided attention required for learning. Orientation detection began to improve only after the central identification task was mastered.

The fact that subjects implicitly chose a sequential learning strategy when initially trained with the dual-task paradigm may explain why separate training is so effective (Fig. 2). It conforms to the apparent inherent limitation of being able to learn only one of these tasks at a time. However, there is an advantage to the explicitly separate training regime in that the order of learning is under the control of the experimenter-trainer. This paradigm is also the common routine of beginning piano students—drilling first with one hand, then the other, and finally rehearsing with both together.

Having found a long period during which letter identification was already nearly perfect but no improvement in orientation detection was apparent, we wondered whether subjects were not trying their best, and instead “forgetting” about the detection task. Is attention during learning in some way under subjects’ control? To test this possibility, we selected a few subjects who showed no improvement in orientation detection during their first three training sessions ($n = 4$; 8 of 20 subjects did not learn the orientation detection task even after three practice sessions; 2 dropped out, 2 learned spontaneously in their fourth or fifth sessions, and 4 were selected). Just before the fourth session, the experimenter addressed them, saying, “Could you please try harder with the pop-out task, yet don’t forget to also perform the letter task.” This instruction made 2 of the 4 subjects voluntarily change their priorities. Their orientation detection immediately began to improve. However, their performance on the letter task regressed to chance level, as illustrated in Figure 5. (A 3rd subject improved only after a delay of 500 trials and did not show degradation in letter identification; the 4th did not improve through four more sessions.) The trade-off confirms that subjects cannot improve on both tasks simultaneously. The parameter that may be flexibly affected by instructions is the set of internal priorities, determining which of the two tasks will be learned first.

Fig. 4. Results for Experiment 4: Percentage correct for 4 subjects after training with the dual-task condition. Two of these subjects were instructed to perform the orientation detection (pop-out) task first on each trial, and 2 were instructed to perform the letter identification task first. Vertical bars separate testing sessions. SOA = stimulus-to-mask onset asynchrony.

GENERAL DISCUSSION

Subjects overtrained on odd-element orientation detection were strongly affected by introduction of a concurrent central-letter identification task (Experiment 1). Thus, training of a single simple task speeds its performance but does not free it from attentional bottlenecks. Still, subsequent dual-task practice did bring about successful concurrent performance, showing that interference can be overcome. Interestingly, training with each task separately (Experiment 2) induced nearly as good concurrent performance, indicating that interference reduction did not derive mainly from better central executive control. Even successful dual-task performance does not express independent processing, because making the higher-priority task harder reintroduced cross-task interference (Experiment 3). This conclusion is strengthened by the fact that the subjects in Experiment 3 were trained with the dual-task paradigm, so they had the greatest chance of achieving independence.

An interesting finding is that task priority is consistent and does not change from novice to expert. The higher-priority task is both learned first (Experiment 4) and performed first, and it can hamper performance of the second task but not be hampered by it.

We explored the power and limitations of training and sharpened the distinction between increased efficiency, revealed by reduced pro-

cessing time, and increased automaticity, revealed by decreased intertask interference. Although training may improve both, the underlying mechanisms may not be the same. Performance efficiency is a property of each task, and indeed practicing orientation detection improves its performance speed. Yet even massive training did not abolish the sensitivity to interference: Single-task training does not eliminate the processing bottleneck, nor does it necessarily change task priorities. Interference is a property of two tasks and their relative priorities. Thus, a prerequisite for reduced interference for the lower-priority task is increased efficiency of the higher-priority task, though this may not suffice.

Increased efficiency will result from any mechanism that reduces the time needed for sequentially performed task processes. Interference will be reduced, however, only if processing time is reduced at or before the bottleneck that is shared with the other task. Theories that do not distinguish between efficiency and automaticity will not necessarily account for both phenomena. For example, in Logan's (1988) instance theory, learned efficiency and automaticity are integrally connected: The power law and decreased interference both derive from the increased number of recalled instances. Because the process that is sped up in instance theory follows the main attention-demanding stimulus-encoding bottleneck, this theory accounts for increased efficiency, but not for the decreased interference between our tasks.

What are the sites of improvement underlying increased efficiency

Fig. 5. Percentage correct on the orientation detection (pop-out) and letter identification tasks for 2 slow learners in Experiment 4. Following three practice sessions during which their orientation detection performance remained at chance level, these subjects were reminded to attend to the orientation detection task. Vertical bars separate testing sessions. SOA = stimulus-to-mask onset asynchrony.

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and automaticity in the current study? It has been observed recently that processes encoding stimuli in working memory pose a bottleneck in dual-task performance even when the two tasks involve different modalities (Jolicoeur, 1999). It follows that these processes should pose a bottleneck for two visual tasks both using oriented lines. Because the site of improvement that results in decreased intertask interference must be at or before the major bottleneck, we conclude that learning occurs at stages that precede stimulus encoding, in agreement with several previous theories of perceptual learning (see review by Ahissar & Hochstein, 1998). Learning reduces the amount of encoding and processing by gradually discarding more and more irrelevant information (Haider & Frensch, 1996), or facilitates attentional access to representations that yield successful performance (e.g., Ahissar & Hochstein, 1997b). Previous findings that learning is specific to basic features of the visually trained stimuli are also consistent with the conclusion that learning occurs at a low cortical level.

This conclusion is also supported by our current finding that separate task training reduces most intertask interference. In addition, this finding indicates that initial intertask interference cannot be attributed to incompatibilities (Navon & Miller, 1987). Incompatibilities between task demands should not be eliminated without specific dual-task practice.

In summary, we gave observers massive training with simple visual tasks and examined subsequent concurrent performance. As expected from daily experience, ultimately observers managed to perform both tasks successfully. Yet the major mechanism underlying this success was not the gradual elimination of initial attentional bottlenecks, as one might expect from introspection. Neither was improvement the result of learned coordination by a central executive mechanism, as one might expect from people's ability to maneuver in complex conditions. Rather, attentive learning of the tasks, one at a time, resulted in more efficient stimulus encoding, yielding apparently autonomous behavior even though initial attentional constraints remained.

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